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Effect of Water Temperature on the Mechanical Properties of Water Quenched Medium Carbon Steel

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Abstract
The effect of water temperature on the hardness and impact strength of water quenched medium carbon steel was investigated. Two medium carbon steel, 0.33 wt % C and 0.42 wt % C, were heated to 900 ^{o}C and quenched in water at temperatures ranging from 35 ^{o}C (room temperature) to 95 ^{o}C. The results showed that hardness was reduced by over 18% and impact strength was improved by over 50%. The hard martensite structure which usually makes quenched steels highly brittle and of low toughness was replaced by tempered martensite structures thereby impacting better mechanical properties in the steel.

Keywords: Water quenched temperature, Thermal Diffusivity, Hardness, Toughness

1. Introduction

Water quenching is probably the oldest heat treatment process used by man to harden steel. It can be described as the rapid cooling of metal from the solution treating temperature, usually in the range of 845^{o}C to 870^{o}C for steels. Quenching is usually performed in order to prevent ferrite or pearlite precipitation and facilitate the formation of martensite or bainite, [1] . In the hardened condition, steel should have 100% martensite to attain maximum yield strength,[3]. The severity of water makes the hardened steels brittle and in some cases developed internal cracks thus limiting their engineering application. These shortcomings of water quenched steels have almost made the phrase 'water quenched and tempered' a form of heat treatment, since all water quenched steel are tempered. With tempering, the properties of quench steel could be modified to decrease hardness and increase ductility and impact strength,[3]. Another way to minimized distortion in dimensions and cracking during quenching was to minimize the temperature differences between different areas of a part (or sample). This often requires the use of oil or aqueous polymer solutions to moderate the heat transferred during quenching, [1]. Researchers have shown that mineral and vegetable oils could compete favorably with water as steel quenchant producing similar hardness with higher impact strength,[7]. Neem seed oil and engine oil have also been proven to be good quenchants for plain carbon steel and ductile cast iron. They gave hardness values close to those of water quenched samples while their impact strength were higher,[11]. The use of bitumen as a suitable quenching medium has also been reported. The results obtained by quenching medium carbon steel in hot bitumen was compared with those of water quenched steel tempered at different temperatures. Quenching in bitumen gave better toughness and tensile properties while the hardness values were almost the same,[6,8]. The report on bitumen stated that the experiments were carried out in a fume cupboard due to the health hazard involved in the inhalation of bitumen fume and fire safety related issues. The works on vegetable oils, neem seed oil, engine oil and other mineral oils made little or no mention of the health and safety hazards involved in working with the oils as quenchants,[4]. Water is the cheapest, most abundant and safest of all the media used in the hardening of plain carbon steel. Therefore, it becomes imperative to explore all the thermodynamic properties of water with a view to overcoming the defects in water quenched plain carbon steel. This work is aimed at investigating the effect of water temperature on the hardness and toughness of water quenched medium carbon steel.

2. Materials and Methods

The steel samples used for the study are from Delta Steel Rolling Mill, Nigeria. The steel samples are used for, among other things, the production of slip gauges and other inspection gauges. There chemical composition is shown in Table 1.The quenchant used is water.

The equipment used include: Lathe machine, electric water heater, electric furnace, Rockwell hardness machine, Hounsfield balanced impact tester, Hounsfield notching machine and Hounsfield Tensometer. Thirty five test piece were machined from each of sample A (0.33%C) and sample B (0.42%C) for hardness, impact and tensile test. Seven cylindrical test pieces of dimension Φ10mm × 10mm, from each sample, were machined, grind and polished for digital Rockwell hardness test. Fourteen test pieces of dimension Φ8mm × 45 mm with a V notch 1.9 mm deep, 45^{o}

tapered from its root was made at the centre of each impact test piece. Another fourteen test pieces of gauge length dimension of Φ4.8mm ×25 mm [10] were machined from each sample for the tensile test.

The samples were normalized, and then austenitized in batches at 900°C for one hour. Each batch, comprising two impact, one hardness and two tensile test pieces, was then quenched in water at temperatures of 35°C, 50 °C, 65 °C, 80°C and 95 °C.

To determine the minimum amount of water required to satisfactorily quenched the steel samples without rising the water temperature by more than 1°C, the first law of thermodynamic was applied

Mass of an impact test sample, M_1 = 17.82g

Mass of a tensile test sample, M_2 = 6.59g

Mass of a hardness test sample, M_3 = 6.20g

Mass of water required for quenching operation, M_w

SHC of steel, C_s = 0.42 J/ gK

SHC of water, C_w = 4.2 J/ gK

Where,

SHC = specific heat capacity

Temperature of test pieces from furnace, T_1= 900°C

Initial Temperature of water, T_2 = 35°C

Final temperature of mixture, T_3 = 36°C

Total mass of pieces in one batch, M

$$M = 2*M_1 + 2*M_2 + M_3 = 55.02g$$

Assuming no heat is lost to the surrounding, from the first law of thermodynamics, heat gained by the quenching medium is equal to the lost by the test pieces [9].

$$MC_s (T_1 - T_3) = M_w C_w (T_3 - T_2) \quad \ldots\ldots (1)$$

$$55.02 *0.42*(900-36) = M_{w1}*4.2*(36-35)$$

$$M_w = 4753.73g$$

But volume = mass/density

Using density of water as 1gcm^{-3}

Hence, the volume of water needed to quench the 1st batch was 4.76 litres.

Similarly, the volume of water required to quench the 2nd batch at T_2= 50°C was 4.68 litres. While the volume of water required to quench the 3rd, 4th and 5th batches at initial temperature 65°C, 80°C and 95°C respectively were 4.6, 4.52 and 4.43 litres respectively.

The actual volume of water used for quenching each batch was the calculated volume plus two litres. The mixture was stirred continuously for 3 minutes then allowed to cold to room temperature.

The as-quenched pieces were subjected to standard hardness, impact and tensile test.

The Rockwell hardness testing machine on the "A" scale was used to determine the hardness values. The samples were properly flattened and polished before the diamond indenter was brought in contact with the test piece.

The impact test was conducted on the Hounsfield balanced impact machine. The hammer was moved out of position by raising the pawl release lever. The inner tup was lifted to the right while the outer tup was moved upward to the left. The test piece was then inserted into the slot in the inner tup by pulling the notch register backward and ensuring that the V notch was actually engaged. The hammer was then threw over smartly and the reading taken by observing the pointer.

The tensile test was conducted on the Hounsfield Tensometer. The test pieces were firmly held in the chucks of the machine. A continuous load was manually applied while the load-extension curve was traced on a graph attached to the drum. The percentage elongation and percentage reduction of area were measured using gauges,[10]

3. Results and Discussion

The hardness values of the different water quenched conditions for both samples are illustrated in Figure 1.
The hardness values of sample B were higher than the corresponding values of sample A for all the five temperatures. This might be due to the fact that the percentage of carbon in sample B is higher than in sample A,[5]. The highest hardness values of 72.6 HRA and 81.3 HRA for sample A and sample B respectively was attained at the water temperature of 65 °C. While the lowest hardness values for both samples were recorded at 95 °C. This may mean that thermal diffusivity of the steels in water was highest at 65 °C and lowest at 95 °C, [2] .
The impact strength fluctuates as quenching medium temperature increased from the assumed room temperature of 35 °C to the pre-boiling temperature of 95 °C as shown in Figure 2.

The toughness of the sample A is higher than that of sample B. This is likely due to the lower carbon content of sample A, [5]. The highest impact energy of 46.69J and 40.12J recorded for sample A and sample B respectively were at the water temperature of 95°C. This further strengthen the earlier assertion that the thermal diffusivity of the steels in water was least at 95°C,[2]. This implies that it took a longer time for the heat in the steels to flow out to the surroundings, thereby creating room for the hard martensitic structure, [3] initially formed in the core of the steels to be slightly tempered. Since tempering always increase the toughness of water quenched steel, [5]

Figure 3, Figure 4 and Figure 5 show the results of tensile strength, percentage elongation and percentage reduction in area respectively for sample A and sample B.
Looking at the high values of the percentage elongation and percentage reduction in area, one could argue that the best tensile properties for both samples were achieved at the quenching temperature of 95 °C. This may not also be unconnected to the low thermal diffusivity of the steels in water at 95 °C.

4. Conclusion

From the results of the study the following conclusion can be drawn.

1. The toughness of water quenched medium carbon steels can be greatly improved with only slight decrease in hardness by raising the temperature of the water to 95 °C
2. Where hardness is the targeted property of a water quenched steel, the best results would be achieved by quenching at 65 °C
3. Water quenching can be used to achieve better mechanical properties for plain carbon steels without wasting additional energy tempering or quenching in some hazardous and expensive oils.

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Table 1: Chemical Composition of the Steel Samples

	Sample A (wt. %)	Sample B (wt. %)
C	0.32	0.42
Mn	0.68	0.53
Si	0.24	0.17
P	0.032	0.031
S	0.04	0.048
Cr	0.17	0.18
Ni	0.12	0.11
Cu	0.30	0.32
V	0.003	0.003
Al	0.46	0.40
Sn	0.024	0.021
Ti	0.001	0.001

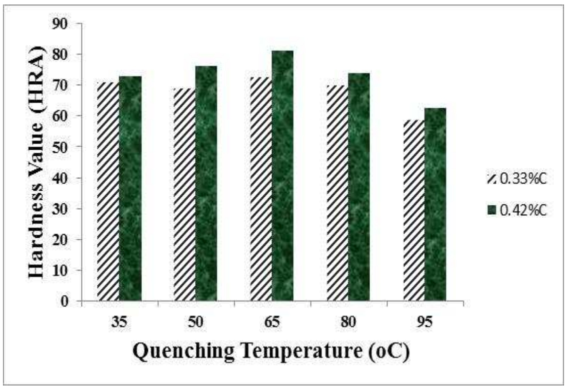

Figure 1: Effect of Water Temperature on the Hardness of the Quenched Steel Samples

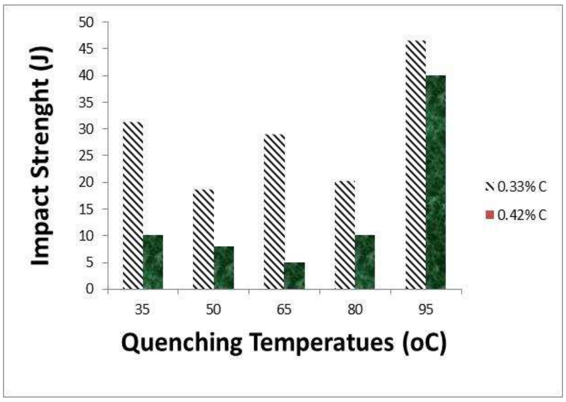

Figure 2: Effect of Water Temperature on the Impact Strength of the Quenched Steel Samples

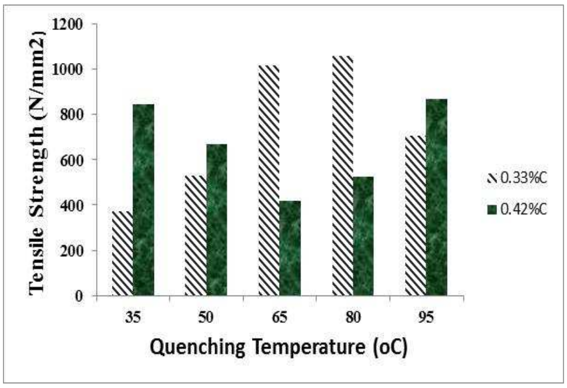

Figure 3: Effect of Water Temperature on the Tensile Strength of the Quenched Steel Samples

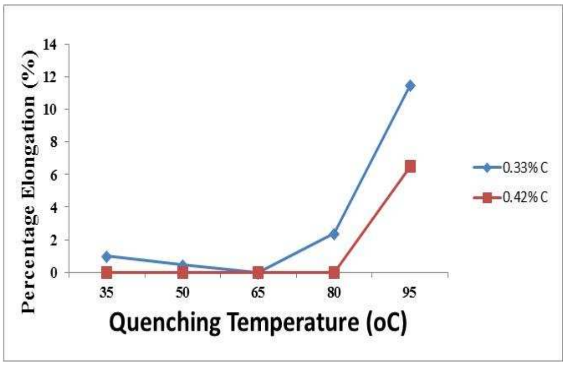

Figure 4: Effect of Water Temperature on the % Elongation of the Quenched Steel Samples

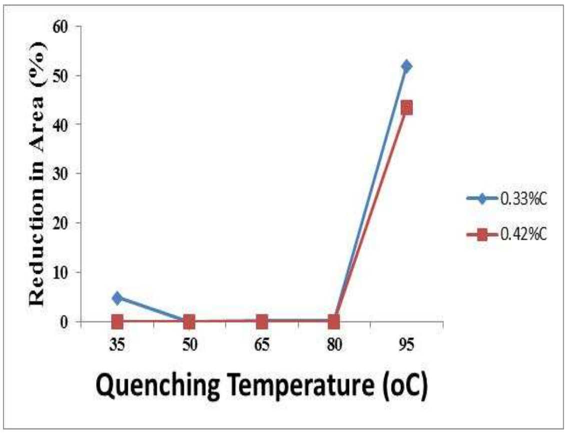

Figure 5: Effect of Water Temperature on the % Reduction in Area of the Quenched Steel Samples